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THE USE OF SELF-FOCUSING IN THE PREVENTION OF LASER-INDUCED DAMAGE

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Laser-induced breakdown in thin foils and gasses have been used to limit transmission at high laser powers in order to prevent damage to sensitive optical components in complex laser systems. In this paper we report results of using self-focusing in liquids to produce laser-induced breakdown and phase aberrations which in turn limit the transmitted power. Optical self-action in CS_2 and other liquids was used to make a power limiting device with psec response time. This device has linear response near unity transmission for input power below P_c, which is of the order of the critical power for self-focusing, and limits the transmitted power to a nearly constant value for input power greater than P_c. The onset of nonlinear transmission was adjusted by mixing various liquids to adjust n_2. Experimental results using linearly and circularly polarized, 40 psec (FWHM) pulses at 1.06 μm are presented.

Key words: self-focusing; laser-induced breakdown; nonlinear absorption; nonlinear refraction; Kerr liquids.

1. Introduction

Laser-induced breakdown and self-focusing are usually associated with catroscophic damage to optical components. In this paper we describe a technique by which these phenomena can be used in the prevention of laser-induced damage. The basic concept is to use intensity dependent refraction (self-focusing) and intensity dependent absorption (associated with laser-induced breakdown) to make a passive optical device which has high transmission for low input power but low transmission for high input power. Such a device can be considered an optical power limiter or a nonlinear optical switch. Our results show that a device with psec response time can be made. Possible uses of this device include the protection of detectors used to study pre-lasing in large oscillator-amplifier laser systems and to optically isolate sensitive oscillator components from back propagating high power beams from amplifier sections.

2. Passive, Nonlinear Power Limiter Concept

Figure 1 is a schematic of the device which we call a nonlinear power limiter (NPL). The solid lines trace the input beam for low input power. The beam is focused by lens L_1 into a material with high nonlinear refractive index, n_2. For low input powers the light is imaged by lens L_2 through a

pinhole onto detector D_4. As the input power is increased to approximately P_2, the critical power for self-focusing, [1] the beam undergoes severe phase abberations, (i.e., nonlinear refraction), and consequently the waist from lens L_1 is no longer in the proper location to be reimaged by L_2 onto detector D_4. The high power situation is shown schematically by the dotted lines.

The NPL shown in figure 1 has been previously demonstrated using nsec pulses at 1.06 μm with CS_2 as the nonlinear medium [2] and is similar to the arrangement used by Bjorkholm et al. [3] to make a passive bystable device. In this work we demonstrated the power limiting feature of this concept for psec pulses at 1.06 μm. Various nonlinear media were investigated including CS_2, nitrobenzene and mixtures of these liquids in ethanol. The laser source used in this work was a mode-locked Nd:YAG laser operated at 1.06 μm with Gaussian spatial and temporal profiles. The single pulse energy was variable up to approximately 10 mJ. The temporal puslewidth was variable from 40 psec to 300 psec, however, all data presented in this paper corresponds to pulsewidths of 40 psec (FWHM). The laser system and associated diagnostic equipment is described in greater detail in Ref. [4].

Figure 2 shows the power limiting capability of the NPL using CS_2 as the nonlinear medium and linearly polarized light. Note that the output of the device (D_4) is effectively clamped, even for the maximum input of approximately 4×10^6 W. The "step-function" like transmission for low input power is the region of linear response. The linear response for low input power and the onset of the nonlinear response are shown more clearly in figure 3 in which the horizontal scale (input power) has been expanded. Note that the device transmission is linear for input power lower than approximately 26 kW and is clamped for higher input powers. CS_2 is highly transparent at 1.06 μm so with the exception of Fresnel reflection losses (which can be avoided with antireflection coating) the device transmitts all the incident power until the cutoff power is reached.

3. Power Limiting Mechanisms

The mechanisms for the limiting action shown in figures 2 and 3 were investigated by measurement of the threshold for nonlinear transmission (P_c) as a function of n_2 (nonlinear refractive index), the f/no. of lens L_1 and of the polarization of the incident laser radiation. These masurements were conducted with and without the limiting aperature in front of detector D_4. The results of these measurements indicate that the mechanisms which limit the transmission of the NPL are intensity dependent refraction (self-focusing) and intensity dependent absorption associated with laser-induced breakdown (initiated by self-focusing).

Analysis of the data shown in figure 3 and two additional experiments under identical conditions indicate that the critical power for the onset of nonlinear transmission (P_c) is 26 ± 3 kW for CS_2. The data points shown in figure 3 and the other plots in this paper are the averages of the reading on detector D_4 for 5 laser shots. P_c was determined by monitoring the ratio the reading on D_4 to the input power. The standard deviation of this ratio for a group of 5 shots was relatively small for powers significantly above or below P_c. The standard deviation of this ratio increased by as much as an order of magnitude at P_c. Thus, monitoring the standard deviation in the ratio of the reading on detector D_4 to the input power was a sensitive and reliable method of determining P_c.

Marburger [1] has solved the nonlinear wave equation for the case of a focused Gaussian beam. The least critical power for a self-trapped mode is $P_{c1} = 3.72\ P_1$ where

$$P_1 = \frac{c\lambda^2}{32\pi^2 n_2}$$ and where n_2 = nonlinear index of refraction, λ = laser wavelength, c = speed of light

The beam will self-focus for powers greater than a critical power P_2 which is slightly higher than P_{c1} but is taken to be equal to P_{c1} for Gaussian beams [1]. Assuming that our measured value of P_c corresponds to P_2 we then calculate n_2 for CS_2 at 1.06 μm to be $1.5 \pm 0.3 \times 10^{-11}$ esu. The $\pm 0.3 \times 10^{-11}$ esu total uncertainty includes the ±15% absolute uncertainty in the power measurement and the ±13% relative uncertainty in P_c. The total uncertainty is calculated assuming the absolute errors in power measurement and relative error in determining P_c are uncorrelated. This value of n_2 is in excellent agreement with the value of $1.3 \pm 0.3 \times 10^{-11}$ esu for CS_2 at 1.06 μm deduced from direct interferometric measurements by Witte et al. [5] at 1.32 μm using 700 psec pulses.

The measurements by Witte et al. [5] are the only known direct measurement of n_2 in CS_2 at optical frequencies. Moran et al. [6] inferred a value of $1.10 \pm 0.33 \times 10^{-11}$ esu for CS_2 at 1.06 μm by comparing their direct measurement of n_2 for ED-2 glass with independent measurements of n_2 for ED-2 glass by Bliss et al. [7] and relative measurements of n_2 for ED-2 glass and CS_2 by Owyoung [8]. Shen [9] and Owyoung [8] used the d.c. Kerr constant for CS_2 to calculate n_2 for CS_2 at 0.67 μm and 0.694 μm. When extrapolated to 1.06 μm Shen and Owyoung's values give n_2 at 1.06 μm of 2×10^{-11} esu and 2.55×10^{-11} esu respectively.

The n_2 value for CS_2 at 1.06 μm deduced from the measurements of P_c in this work and the n_2 values determined by direct interferometric measurements have overlapping error bars and are therefore in reasonable agreement. However, there are several tests for self-focusing which do not depend on knowing the absolute value of n_2 and are independent of absolute errors in the input power measurements. In the paragraphs that follow we describe the results of several of these tests which confirm that self-focusing was the primary mechanism for the limiting action shown in Figs. 2 and 3.

Self-focusing theory [1] predicts that $P_2 \sim 1/n_2$. Prior work [10] has shown that one can vary n_2 by mixing CS_2 with ethanol (which has a very low n_2). A 50-50 mixture of CS_2 and ethanol has an n_2 equal to approximately one-half that of neat CS_2. Therefore for self-focusing in a 50-50 mixture one would expect that the onset of the power limiting would occur at a power approximately twice as high as required for neat CS_2. The data shown in figure 4 for this mixture indicates that the onset of limiting occurs at approximately 58 ± 7 kW which is in good agreement with the predictions of self-focusing theory. Note that this result means that one can adjust the output of the NPL by simply mixing a high n_2 material with a low n_2 material to adjust P_2 to the desired level.

The data shown in Figs. 2 to 4 were taken using a 37 mm focal length lens (L_1) used at f/7.9 to focus the light into the nonlinear medium. A critical test for self-focusing is to vary the focal length of L_1. The onset of self-focusing is dependent on the power rather than the input intensity and thus the onset of nonlinear transmission will be independent of the focal length of L_1 if self-focusing is the critical mechanism. Figure 5 is a plot of D_4 versus input power with the 37 mm focal lengths lens replaced by a 75 mm focal length lens (used at f/16). The cutoff power is approximately the same as that shown in figure 3 (26 ± 3 kW). An intensity dependent process would have required a factor of four increase in input power and one can see from figures 3 and 5 that the critical power is independent of the focal lengths of lens L_1 within the experimental uncertainty.

The relatively large n_2 values for materials such as CS_2 and nitrobenzene are due to the orientational dependence of the linear refractive index of these molecules. Thus, the self-focusing observed in these materials is due to optically induced ordering of the molecules, i.e., the AC Kerr effect. Therefore, self-focusing in these materials should be critically dependent on the polarization of the incident light. Figure 6 is a plot of D_4 versus P for circularly polarized light. P_c, the cutoff power for linear polarized light, is approximately 26 ± 3 kW while that for circularly polarized light, P_{cc} is approximately 47 ± 4 kW. Figure 7 is a plot of D_4 versus P for the 50-50 mixture of CS_2 and ethanol using circularly polarized light. For this case P_{cc} = 125 ± 10 kW as compared to 58 ± 7 kW for linear polarization and the same mixture. Similar measurements in neat nitrobenzene yielded P_c = 72 ± 7 kW and P_{cc} = 133 ± 13 for linear and circular polarization respectively. The average ratio of P_{cc} to P_c for the various measurements was 1.9 ± 0.2. This compares favorably with the value of 2.0 found by Close et al. [11] and Wang [12] for the ratio of the critical power for self-focusing in CS_2 using completely different techniques and nanosecond ruby laser pulses (λ = 0.694 μm). However, theoretical calculations by Shen [9] predicts that the ratio of n_2 for circular polarization to the n_2 for linear polarization should be 4 for self-focusing which is due to molecular reorientation. The approximate factor of 2 difference between the measured ratio in this work and Refs. 11 and 12 and the theoretical value is not understood at this time. Feldman et al. [13] measured a ratio of approximately 1.1 to 1.3 for various solids for which electrostriction and electronic self-focusing are thought to be important. Hellwarth [14] and Wang [12] have pointed out that the circular to linear polarization ratio should be related to the ratios of the various components of $\chi^{(3)}$, the third-order optical susceptibility. While there is considerable debate in the literature as to what the exact ratio of n_2 for circular and linear polarization should be there is agreement that n_2 for circular polarization is less than that for linear polarization.

The dependence of P_c on n_2, the beam polarization and the focal length of lens L_1 are all consistent with the idea that the observed nonlinear transmission is due to the onset of self-focusing. Additionally we observed bright "streamers" of flashes (due to laser-induced breakdown) for input power substantially above P_c which suggests self-trapping or a moving self-focus position. These "streamers" are evidence that self-focusing is the mechanism for the self-limiting action of the NPL, however, they also suggest that the observed limiting behavior may be due to the nonlinear absorption in the laser induced plasma (initiated by self-focusing). The effects of laser-induced breakdown were investigated by removing the pinhole in front of the detector (D_4 in fig. 1) so that all the light transmitted through the cell was intercepted by the detector. The results are shown in figure 8.

The results shown in figure 8 indicate that nonlinear absorption is taking place, however, the onset of the nonlinear absorption is associated with the same input power as observed in figure 3. The test previously described for self-focusing were repeated without the pinhole in place and the onset of nonlinear behavior varied as predicted by self-focusing theory. We conclude that the observed clamping of the output of the NPL is due to both nonlinear refraction and nonlinear absorption and that both mechanisms are associated with self-focusing.

The above results indicate that P_c, the critical power for the onset of nonlinear transmission, has the polarization, focal length and n_2 dependence consistent with self-focusing. These experiments were repeated with neat ethanol and $CC\ell_4$ substituted for the high n_2 material. Figures 9 and 10 are the results for ethanol using the 75 mm focal length lens for L_1 for linear and circular polarization respectively. Figure 11 is a similar plot for $CC\ell_4$ for linear polarization. Table 1 summarizes the resulting P_c's for this material and the other materials tested. The ratio of P_c for the 37 mm and 75

mm focal length lenses is 4.1 ± 0.4 whereas the square of the focal lengths of the lenses is 4.11. Therefore, the onset of nonlinear behavior is intensity dependent instead of power dependent as in the Kerr liquids. The data in table 1 indicate that the critical power for linear (P_c) and circular (P_{cc}) polarization are approximately equal for ethanol and $CC\ell_4$. The lack of polarization dependence of P_c and the dependence of P_c on the focal length of lens L_1 confirms that the nonlinear transmission in ethanol and $CC\ell_4$ is due to nonlinear absorption in the laser - induced plasma which accompanies dielectric breakdown in these materials. From table 1 we see that the ratios of P_c for CS_2 to P_c for ethanol and $CC\ell_4$ are approximately 0.020 and 0.063 respectively. Hellwarth et al. [15] determined that the ratio of the n_2 for CS_2 to that of $CC\ell_4$ is 56 ± 6 at 0.694 μm, indicating that P_c ($CC\ell_4$) = 56 P_c (CS_2). This implies that P_c ($CC\ell_4$) due to self-focusing should be approximately 1460 kW, which is more than a factor of 3.5 greater than the value required to induce breakdown in this material. The ratio of the optical Kerr constant for ethanol to that of CS_2 is 0.0064 [9] which implies that P_c (ethanol) due to self-focusing should be approximately 4060 kW, a factor of 3.1 greater than that required to induce breakdown. Thus, one would expect that self-focusing was not a factor in the observed nonlinear transmission of these two materials.

4. Pulsewidth Dependence of the NPL

The molecular reorientational relaxation time for CS_2 is approximately 2.1 psec [16] and therefore much shorter than the pulsewidth used in this work. P_c and P_{cc} for CS_2 are expected to be independent of pulsewidth for pulsewidths substantially longer than 2 psec. P_c for similar measurements in Ref. 10 at 1.06 μm with 9 nsec pulses was 14 ± 1 kW. More recent measurements [17] using the same laser system as in Ref. 10 resulted in P_c = 20 ± 3 kW which is in reasonable agreement with the 40 psec data reported here. The large discrepancy in the nsec data ia probably due to errors in power measurements in the earlier work (Ref. 10) due to unresolved partial mode-locking of the Q-switched pulse or a calibration error.

The ratio of P_c (nitrobenzene) to P_c (CS_2) from table 1 is 2.8 ± 0.4 and the corresponding ratio of P_{cc}'s is 2.7 ± 0.4. The ratio predicted by the optical Kerr constant [9] for these materials is 1.23 and the measured ratio for P_c for nsec pulses [10] is 1.8 ± 0.3. Since the molecular relaxation time for nitrobenzene is 44 psec [18] (the same order as the laser pulsewidth in this work) the contribution of molecular reorientation to the n_2 of nitrobenzene should be diminished. The ratio of n_2 for CS_2 to n_2^e, the nonlinear index of nitrobenzene due to electronic self-focusing, is 2.74. We conclude that the P_c and P_{cc} measured for nitrobenzene is primarily due to electronic self-focusing. Thus while P_c and P_{cc} for CS_2 are expected to be much smaller for subpicosecond pulses than the values reported here, the corresponding values for nitrobenzene are expected to be independent of pulsewidth for pulsewidths from 40 psec to the order of 10^{-14} sec. Limiting charactertistics for nitrobenzene for circular polarization and the 37 mm focal length lens are shown in Figs. 12 and 13.

5. Summary

We have demonstrated a device that can be used as a power limiter for the prevention of laser-induced damage. The mechanisms which limit the transmission of this device are intensity dependent refraction (self-focusing) and intensity dependent absorption associated with laser-induced breakdown (initiated by self-focusing). This device, which we call a nonlinear optical switch, has been shown to work for 1.06 μm pulses of 40 psec duration. The ultimate response time for this device is deter-

mined by the response time of the nonlinear medium, e.g., 2 psec for CS_2. A medium in which the dominant nonlinear refraction is electronic is expected to have a response time on the order of 10^{-14} seconds. The advantage of this power limiting technique include rapid response and recovery, completely passive operation, relatively low "turn off" power P_c (26 kW for CS_2) at 1.06 μm and P_c can be adjusted by varying n_2.

This work was supported by North Texas State University faculty research funds, The Robert A. Welch Foundation, the National Science Foundation, and the Office of Naval Research.

TABLE 1

Material	L_1 Focal Length P_c	Linear Polarization P_c in kW	Circular Polarization P_{cc} in kW
CS_2	37 mm	26 ± 3	50 ± 7
CS_2	75 mm	26 ± 3	43 ± 3
CS_2:Ethanol	37 mm	58 ± 7	125 ± 10
Nitrogenzene	37 mm	72 ± 7	133 ± 13
Ethanol	37 mm	350 ± 30	380 ± 20
Ethanol	75 mm	1300 ± 200	1700 ± 20
$CC\ell_4$	37 mm	410 ± 40	466 ± 40

Table 1. P_c and P_{cc} for various materials and focal lengths of lens L_1. Note that the average ratio of P_{cc} to P_c is 1.9 ± 0.2 for CS_2 and the Kerr liquids and 1.2 ± 0.1 for the ethanol and $CC\ell_4$. P_c and P_{cc} is independent of L_1 focal length for the Kerr liquids and scale as the ratio of the focal length squared for ethanol and $CC\ell_4$.

6. References

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Figure Captions

Figure 1. Nonlinear Optical Switch (NPL) Concept. Lens L_1 was a single element lens of "best form" design. The input beam radius (to the $1/e^2$ points of irradiance) was 2.35 mm and the focal length of lens L_1 was 37 mm. L_1 was located so as to produce a focal spot in the middle of the nonlinear cell. L_2 was an 80 mm focal length microscope objective placed approximately 68 mm behind the 12 mm thick cell. This arrangement produced a focal spot of approximately 100 μm diameter which matched the 100 μm diameter aperature located 525 mm behind lens L_2.

Figure 2. Intensity Limiter Response. This is a plot of the results of measurements using CS_2 as the nonlinear medium (NL)in figure 1. The laser source was a Nd:YAG laser operating at 1.06 μm with puslewidth of 40 psec. The region of linear (the nearly vertical line on the extreme left of this graph) response is shown in more detail in figure 3.

Figure 3. The Onset of Nonlinear Transmission. This plot is for the same material (CS_2) and laser source as used for the data in figure 2. Here the horizontal scale has been expanded to show the region of linear response and the onset of nonlineaer transmission ($P_c = 26 \pm 3$ kW). Each data point is an average of 5 shots. P_c was determined by monitoring the standard deviation in reading of detector D_4 in the raw data.

Figure 4. P_c for a 50-50 mixture of CS_2 and ethanol. These data are for linearly polarized light and a 50-50 mixture of CS_2 and ethanol. $P_c = 58 \pm 7$ kW was determined from the increase in the standard deviation in the readings of detector D_4.

Figure 5. Nonlinear power limiter with the focal length of L_1 equal to 75 mm. The nonlinear medium was neat CS_2 and the incident radiation was linearly polarized. For this case $P_c = 26 \pm 3$ kW as in the case where the L_1 focal length was 37 mm.

Figure 6. Nonlinear power limiter with circularly polarized light. These data are for CS_2 with circularly polarized light. L_1 focal length was 37 mm. The cutoff power was determined to be 47 ± 4 kW.

Figure 7. CS_2 - Ethanol, Circular Polarization. The focal length of L_1 was equal to 37 mm. In this case $P_{cc} = 125 \pm 10$ kW.

Figure 8. Linear Polarization, CS_2, 37 mm, f.ℓ. for L_1. The aperature in front of D_4 was removed and the reading on D_4 was measured as a function of input power. Note that the change in slope occurs at $P_c = 26$ kW as in figure 3. The change in slope is due to nonlinear absorption in the laser-induced breakdown that results from the self-focusing.

Figure 9. Linear Polarization, Ethanol, 75 mm f.ℓ. for L_1.

Figure 10. Circular Polarization, Ethanol, 75 mm f.ℓ. for L_1.

Figure 11. Linear Polarization, $CC\ell_4$, 37 mm f.ℓ. for L_1. Note that nonlinear transmission begins at $P_c = 410$ kW but the transmission is not clamped as was the case for the Kerr liquids.

Figure 12. Circular polarization, nitrobenzene, 37 mm f.ℓ. for L.

Figure 13. Circular polarization, nitrobenzene, 37 mm f.ℓ. for L, expanded scale.

NONLINEAR OPTICAL SWITCH

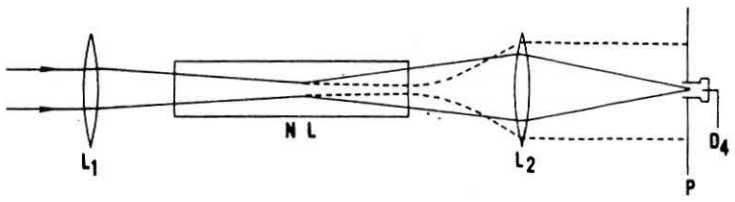
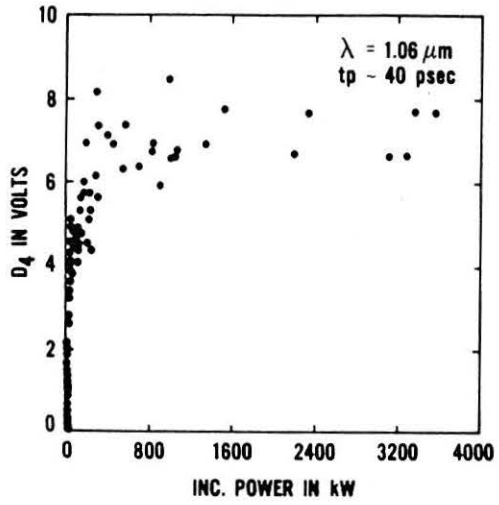


Figure 1



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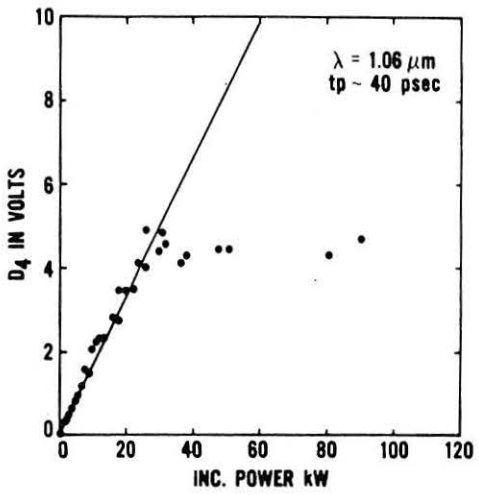

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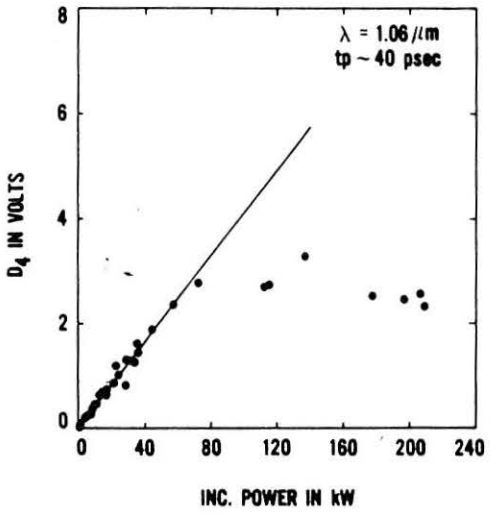

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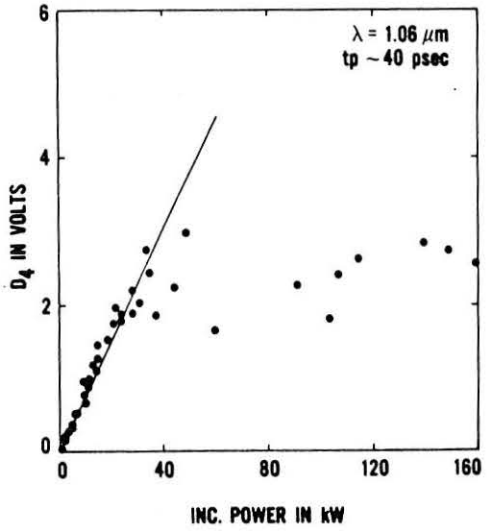

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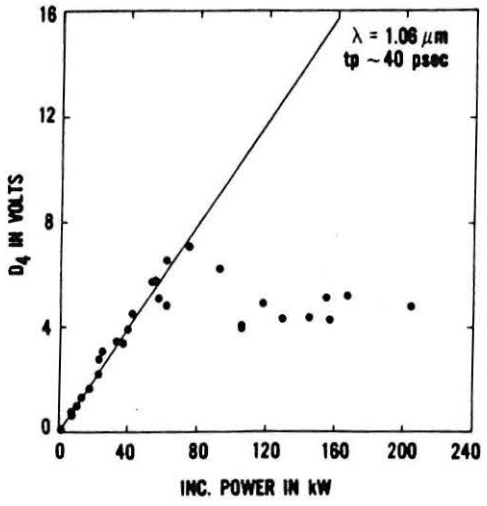
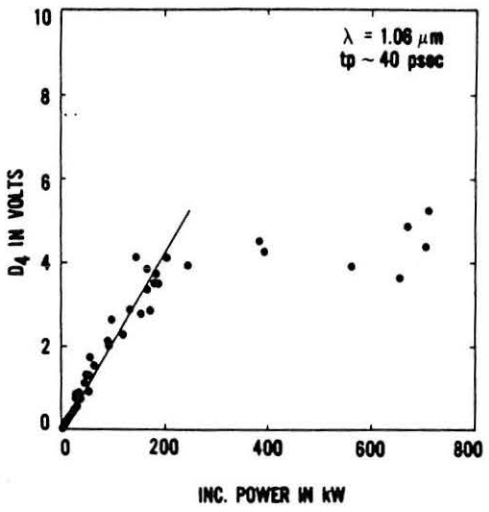


Figure 6



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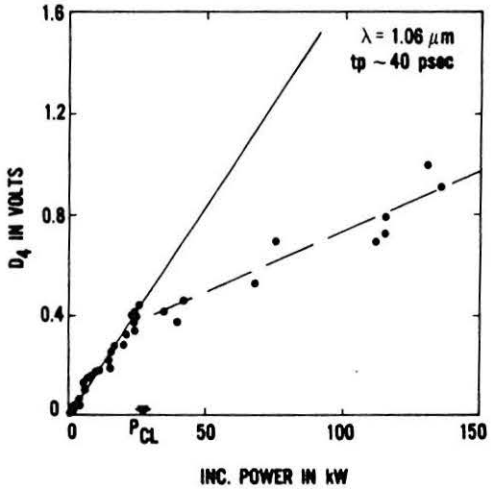

Figure 8

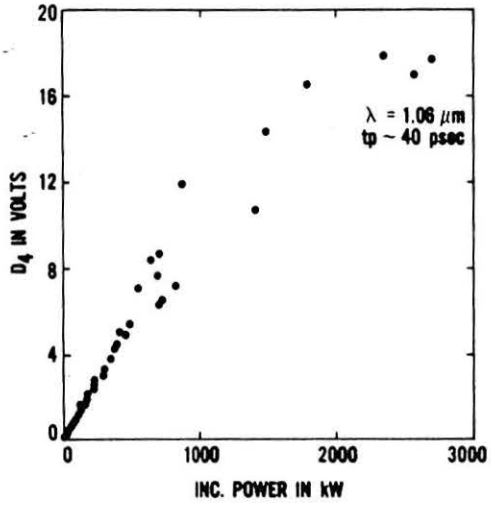

Figure 9

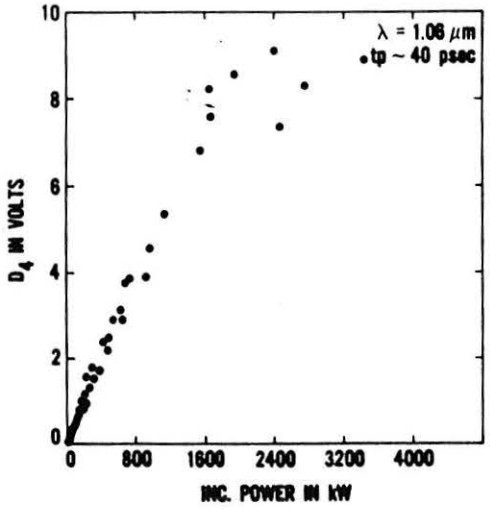

Figure 10

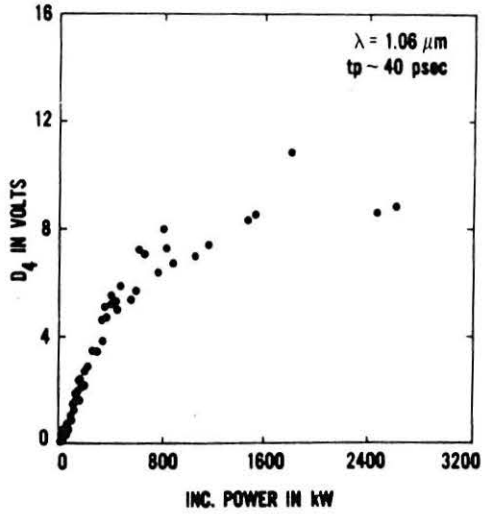

Figure 11

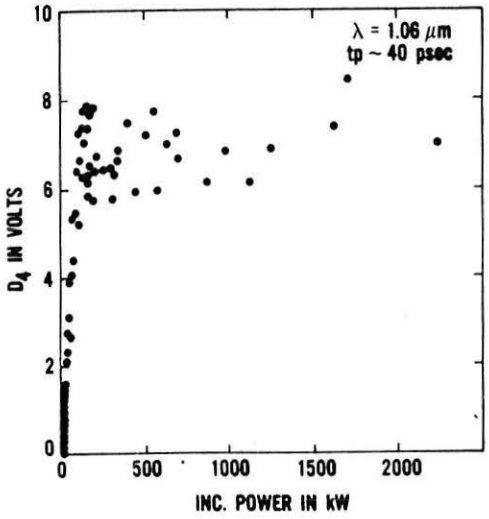

Figure 12

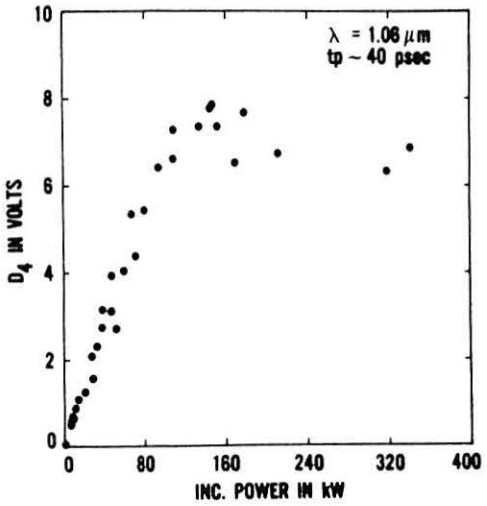

Figure 13

It was pointed out that with large beams the self focusing was not power dependent but is intensity dependent. The analysis given in the paper would have to be modified if one wanted to increase the total power. A device similar to that suggested in this paper was reported as an isolator by Tom Loree in 1974 and should be referred to. Another question was, "What is the spatial intensity of the output beam in the limiting self focusing mode?" The speaker replied that once nonlinear effects occur the output is completely distorted and will not pass the light through the pinhole to the detector.